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ENGINEERED FRACTAL CASCADES FOR FLUID CONTROL APPLICATIONS

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Proceedings, Fractals in Engineering June 25-27, 1997
Arcachon, France
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Introduction

Fluid transporting fractals are ubiquitous in nature and have been described in detail[1,2,3]. However there has been little work engineering such structures for practical applications. The reason may be that the large number of fluid control problems which can be addressed with engineered fractal geometry has not been recognized.

We have designed and constructed a number of fluid transporting fractals for a variety of uses and we wish to advance a group of working hypotheses which suggests a broad range of applications. These hypotheses are:

1. Fluid flow through engineered fractal cascades can exhibit a functional equivalence to turbulence.
   Corollary to 1: Engineered fractal cascades can be designed and used as functional alternatives to turbulence.
2. Fluid flow through engineered fractal cascades can provide controlled formation of macroscopic fluid structure.
3. Fluid flow through engineered fractal cascades can provide dynamic alternation of a fluid structure's gross measure of dimension.

The hypotheses are not strictly independent. Each provides a somewhat different characterization of the same effects. We will hereafter refer to an engineered fractal cascade as an "EFC".

Hypothesis 1

This hypothesis refers to the general scaling and distribution properties of turbulence. As with a free turbulent jet, fluid flow through a fractal cascade, from largest to smallest conduit can undergo a continual reduction of spatial scales and a dissipation of large scale motion into smaller and smaller units. However, the scaling and distribution by an EFC can be controlled while free turbulence is generally considered to be uncontrollable. Another way of describing this difference is to recognize that turbulence exhibits little symmetry while an EFC can be purposely designed to be higher symmetric. These observations suggest that in certain instances the functional utility of turbulence can be maintained but its uncontrollable characteristics avoided.

We have designed a highly symmetric, approximately space filling fractal which serves to illustrate this proposed equivalence (Fig. 1). The similarity to physiological fluid transporting fractals should be evident. Fluid passing from the object's largest inlet conduit to a smallest exit conduit will undergo a continual reduction of the possible range of spatial scales over which the structure and dynamics of free interfluid turbulence can occur. Furthermore, this scaling process can continue as daughter structures are added. With proper conduit design, the Reynolds number will progressively decrease as the structure divides. From the point of view of turbulence/EFC functional equivalence, the object can be viewed conceptually as an engineered, highly symmetric eddy cascade.

Originating applications which make use of this equivalence requires corresponding a function of turbulence with an EFC alternative. As an example, turbulence is closely associated with rapid mixing. By hypothesis 1, rapid mixing without turbulence should be possible with an EFC. For this case, nature has provided a definitive example. It is well known that the fractal characteristics of the circulatory system provide very rapid and efficient low turbulence mixing[4]. It should also be clear that the device in Fig. 1 should mix exiting fluid with surrounding fluid with greater and greater rapidity, and with less and less turbulence involved as daughter structures are added.

We have consequently designed EFCs for such applications as rapid low turbulence mixing, localized pattern mixing of fluids within fluids and controlled turbulence dampening.

Hypothesis 2

This hypothesis refers to the engineering of specific macroscopic fluid structure using EFCs. Fig. 2 illustrates a fractal fluid surface distributor we have designed and implemented for use in industrial scale chromatography. The characteristics of this device include the avoidance of turbulence while quickly forming a homogeneous surface. Fluid flows from a narrow center inlet, then through 6-way, 3-way and 7-way dividers, and finally through a fractal pattern (Cayley tree) where a dimension=2 can be approximated. The fluid is therefore distributed as a circular *surface*. As with the object in Fig. 1, this structure can be thought of as an engineered eddy cascade with scaling and distribution carried out to any desired level (within manufacturing constraints). As bifurcations are added to the fractal pattern, turbulence is progressively reduced at fluid exit and a two dimensional surface is more closely approximated.

As opposed to using turbulence as the scaling and distribution mechanism, the cascade has been designed to be extremely symmetrical. Any individual fluid path from the center to an exit point can be used to generate all other paths, to a close approximation, using symmetry operations. We refer to this property as "universal path symmetry". The resulting path symmetry provides equivalent hydraulics (equivalent flow rate, equivalent time of passage, equivalent pressure drop, etc.) to each exit point. In addition to the symmetry between paths and the scaling symmetry within paths, the structures are used as mirror image distributor and collector pairs within the chromatography columns.

From an engineering point of view, another unusual characteristic is that the devices are, to some extent, invariant to scaling. Larger or smaller devices can be designed by adding or subtracting bifurcations while the symmetry of the object is maintained. We have constructed functional fractal surface distributors ranging in diameter from 15 cm (preparatory chromatography) to 6.7 m (industrial simulated moving bed chromatography).

Hypothesis 3

This hypothesis refers to the dimension altering characteristic of EFCs. For the chromatographic surface distributor discussed above, fluid is converted from an effective dimension of 1 (the incoming small diameter pipe) to an effective dimension of 2 (the surface of fluid which moves down the column). The opposite change of gross fluid dimension is made at the bottom collector. It can be recognized that most engineering unit processes in a fluid processing sequence require this type of conversion of fluid structure. In this respect, EFCs can be seen as useful tools because translation of fluid to, e.g., surfaces or volumes, can be made rapidly in a controlled manner and without resorting to turbulence.

From our experience engineering and implementing fluid transporting fractal cascades, it appears reasonable to suggest that these structures can provide useful control over at least some of the general dynamics of fluids.

References

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Fig. 1. Space filling fluid transporting fractal. Four scales of the fractal are illustrated with each daughter structure 50% the size of its predecessor. Interfluid turbulence is progressively eliminated as smaller scale structure is added. The geometry also exhibits "universal path symmetry" as described in the text for the surface distributor in Fig. 2.

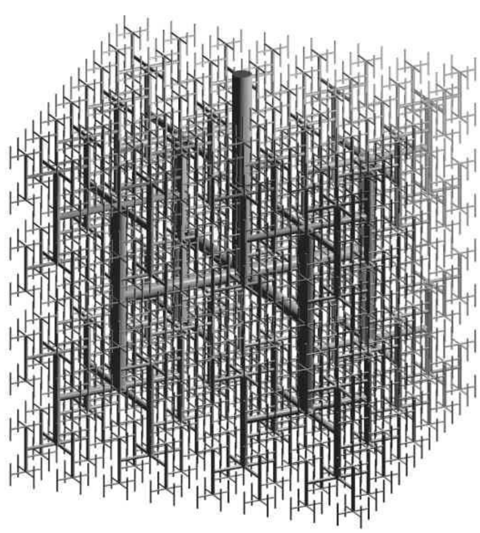

Fig. 2. Fractal surface distributor. Fluid passing through the cascade exits at low turbulence and approximates a surface. The curved conduit is used to aid arranging the pattern on a circular surface while maintaining a close approximation of symmetry for all 8064 pathways. The number of equivalent paths is increased by a factor of four for each iteration of the fractal pattern. The differing sized conduit are on different planes and do not intersect.